

Particle distribution and nuclear stopping in Au-Au collisions at $\sqrt{s_{NN}}=200$ GeV

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The transverse momentum distribution of produced charged particles is investigated for gold-gold collisions at $\sqrt{s_{NN}} = 200$ GeV. A simple parameterization is suggested for the particle distribution based on the nuclear stopping effect. The model can fit very well both the transverse momentum distributions at different pseudo-rapidities and the pseudo-rapidity distributions at different centralities. The ratio of rapidity distributions for peripheral and central collisions is calculated and compared with the data.

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I. INTRODUCTION

Ultra-relativistic heavy ion collision is the only way to study nuclear matters at extremely high temperature and density in the controlled experimental conditions. Such a study can provide information about the internal structure of hadrons and the interactions among partons from which those hadrons are formed. An important quantity for characterizing the properties of the produced particles is the transverse momentum distribution in different rapidity regions. The transverse momentum distribution at mid-rapidity region can tell us the matter density created in heavy ion collisions and that at large rapidity tells us the baryon stopping strength in the collisions. Experimentally, the charged hadrons can be comparatively easily identified and investigated. The multiplicity distribution of charged particle is often used as a global measure of the dynamics of the ultra-relativistic heavy ion collisions. The total multiplicity as a function of rapidity or pseudo-rapidity can be used to measure the nuclear stopping effect in the collisions. Because the stopping effect is directly related to how effectively the kinetic energy of the colliding particles can be converted into thermal one and how many secondaries can be produced in the process, it has been a focus on both nucleon-nuclear and nucleus-nucleus collisions for quite a long time and been studied in various approaches before [1, 2, 3, 4, 5, 6, 7]. Some of the investigations are done at the nucleon level, some others are based on the string model. Since it is not feasible to perform a first-principle parameter-free calculation of the nuclear stopping effect, experimental guidance plays a crucially important role in such studies.

This paper discusses the transverse momentum distributions of emitted particle at the highest energy of the Relativistic High Ion Collider (RHIC) between gold-gold (Au-Au) at $\sqrt{s_{NN}} = 200$ GeV for different centralities and rapidities. We will start from a very simple parameterization for the particle distribution stimulated from momentum degradation effect and fit the experimental data of the transverse momentum distributions for charged particles for different centralities and rapidities. Then the rapidity distributions can be obtained from integration over transverse momentum for different centralities and are compared to the experimental data.

The organization of the paper is as follows. In section II, we will propose a simple parameterization for the invariant particle distributions. Then in section III, we fit the experimental data to our model parameterization. The last section is for a brief conclusion.

II. PARAMETERIZATION FOR THE INVARIANT PARTICLE DISTRIBUTION

More than 30 years ago, the transverse momentum distribution of particles produced at polar angle $\theta = \pi/2$ in high energy proton-proton collisions was suggested [8] as

$$E \frac{d^3\sigma}{dp^3} = A \exp(-\xi^2/2b), \quad (1)$$

from the analogy of Landau's hydrodynamical model, with $\xi = \ln(m_T + p_T)/m$ the transverse rapidity and b a parameter to be determined by fitting the experimental data. Here m is the mass of the produced particle, $m_T = \sqrt{m^2 + p_T^2}$ is the transverse mass. Recently this parameterization was also used in describing the data for nucleus-nucleus collisions at RHIC energy [9] in the mid-rapidity region. At small p_T the above transverse momentum distribution can be approximated by an exponential and the collective flow effect can be extracted if the temperature of phase transition is known. So, The value of b can tell us some information about the collective flow. In recent years, some authors have used the blast wave model to parameterize the transverse momentum distribution, see [10] for example. That model is valid only at low p_T region, since the blast wave is a collective dynamical phenomenon for the produced hot medium and the contribution from hard partons to the particle production cannot be contained in the blast wave model. For the distributions of particles with nonzero longitudinal momentum p_L , no first-principle theory, such as quantum chromodynamics, can be used to derive a formula for the distribution. Therefore, a phenomenological ansatz is needed. In this paper, as usually done in other studies, we simply assume a factorized form for the distribution as

$$E \frac{d^3N}{dp^3} = A \exp(-\xi^2/2b) H(p_L). \quad (2)$$

In a former study [11] of $p-A$ collisions it is shown that the Feynman x_F (or longitudinal momentum p_L) distribution can be approximated by an exponential form. The exponential decrease of the longitudinal momentum distribution is a reflection of the momentum degradation effect from nucleon-nucleon interactions while incident nucleon is penetrating the target. For nucleus-nucleus collisions, one can expect that the distribution may be not too far from that for $p-A$ collisions. Thus we assume

$$H(p_L) \propto \exp(-cp_L^d), \quad (3)$$

with c, d two parameters characterizing the longitudinal momentum degradation effect in nucleus-nucleus collisions. For $p-A$ collisions $d = 1$ [11]. If the physics for the longitudinal momentum degradation is the same in $p-A$ and $A-A$ collisions, $d \simeq 1$ can be expected. A small deviation from $d = 1$ in $A-A$ collisions may be due to the multiple NN collisions, each of which has a different center of mass energy. Here, parameter c is a measure of the strength of longitudinal momentum degradation effect.

By changing variable from rapidity y to pseudo-rapidity η , using $p_L = p_T \sinh(\eta)$, one can get the particle distribution as follows

$$\frac{dN}{2\pi p_T dp_T d\eta} = \frac{Ap_T \cosh(\eta)}{\sqrt{m_T^2 + p_T^2 \sinh^2(\eta)}} \exp\left(-\frac{\ln^2\left(\frac{m_T + p_T}{m}\right)}{2b} - c(p_T \sinh(\eta))^d\right). \quad (4)$$

We assume that the four parameters A, b, c and d depend only on centrality of the collisions at given collision energy, but not on the pseudo-rapidity.

III. CENTRALITY DEPENDENCE OF PARTICLE DISTRIBUTIONS

To determine the parameters for different centralities, we fit the experimental data for produced particles with different centralities and rapidities. For this purpose we choose the data from BRAHMS Collaboration for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [12]. It needs to be mentioned that Eq. (4) is supposed to be valid for a specific species of hadrons with given mass m . In the chosen data, only the spectra of charged particles ($h^+ + h^-$)/2 are given, where all charged particles with different masses are included. If the contribution to the spectra can be parameterized by Eq. (4) for each species of charged hadrons, the distribution for charged particles should be described by the sum of a few terms, each of which is given by Eq. (4). Then there would be too many parameters. Instead, in this paper, we assume that Eq. (4) is still valid for all charged particles, as long as m in Eq. (4) is taken as an effective mass. In principle, the effective mass should depend on the relative contents of

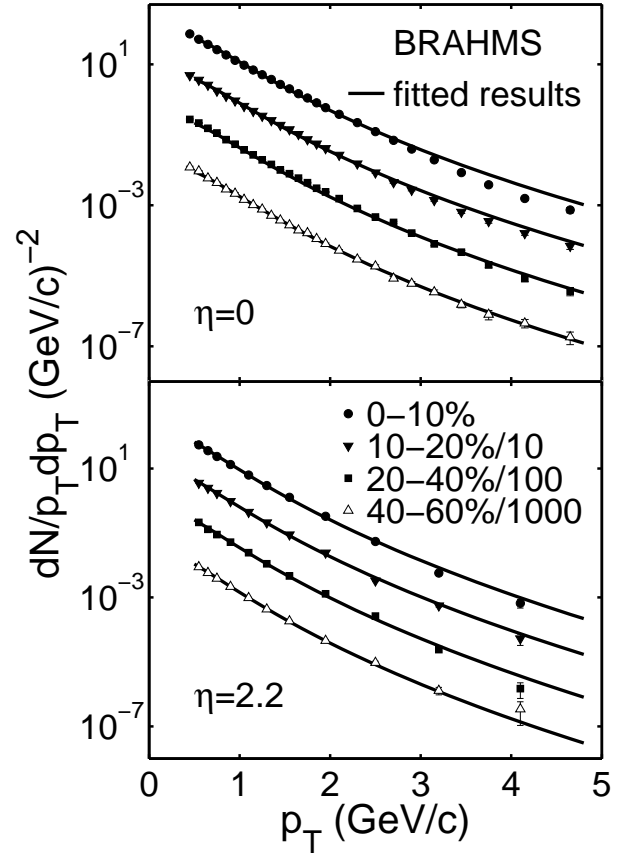


FIG. 1: The charged particle distribution $dN/2\pi p_T dp_T d\eta$ as a function of transverse momentum p_T for Au+Au collisions at pseudo-rapidity $\eta = 0$ (top panel) and $\eta = 2.2$ (bottom panel) for four centralities. The data points are taken from [12]. The solid curves are the fitted results with Eq. (4). For clarity, the spectra have multiplied by the indicated factors.

all charged particles. It is known that the proton to pion ratio is larger than 1 at $p_T \sim 3$ GeV/c [13] and that the kaon to pion ratio is about 0.2 in a wide range of p_T . So the contribution to the distribution of charged particles from protons and kaons will be quite large, especially for central collisions in the mid-rapidity region. Thus the relative contents may be different for collisions at different centralities. Even with the same centrality, the relative contents change with p_T and η . So generally speaking, the value of m is a function of centrality, p_T and η . For simplicity, we assume in this paper that the value of m in Eq. (4) is a constant for all centralities, p_T and η . For this reason, we choose, for different centralities and rapidities, the mass m in Eq. (4) to be 0.51 GeV, about the average mass of proton, kaon and pion. With the charged particle p_T distributions at $\eta = 0$ and 2.2 at the same centrality cut, the fitting process can be completed in two steps. We first fit the experimental distributions of transverse momentum at mid-rapidity ($\eta = 0$) to determine the parameters A and b , then, with fixed A and b , get parameters c and d from fitting transverse momen-

centrality	A	b	c	d
0 ~ 10%	239	0.351	0.0878	0.94
10 ~ 20%	163	0.350	0.0826	0.94
20 ~ 40%	93.3	0.344	0.0818	0.94
40 ~ 60%	39.8	0.340	0.0788	0.94

TABLE I: Values of parameters A , b , c and d for distribution of $dN/2\pi p_T dp_T d\eta$ for four centrality cuts. The fitted data are from [12].

tum distributions at $\eta = 2.2$ at the same centrality. The experimental data chosen have a p_T range from 0.45 to 4.65 GeV/c. We found from fitting that the value of d is 0.94, very close to 1 as expected, and almost the same for different centralities. So we fix $d = 0.94$ for the distributions at other centrality cuts. The fitted results are shown in Fig.1 together with the experimental data from BRAHMS Collaboration for pseudo-rapidity $\eta=0$ and 2.2 at four centralities. It is obvious that the data can be fitted very well to the simple ansatz shown in Eq. (4). The parameters obtained are tabulated in TABLE I.

In TABLE I the value of b decreases slowly from central to peripheral collisions. This means that $R_{CP} = (dN/N_{CP} dp_T)_C / (dN/N_{CP} dp_T)_P$ increases with p_T at $\eta = 0$. For pions, R_{CP} decreases with p_T for p_T not too small, while R_{CP} for protons increases up to p_T about 4 GeV/c [14]. The behavior of R_{CP} for unidentified hadrons is somewhat in between those for pions and protons. The parameter c is an indicator of nuclear stopping in Au-Au collisions. The value of c dictates the difference between the spectra at different pseudo-rapidities at given centrality. The larger the value of c , the bigger the difference, thus the stronger the nuclear stopping effect. One sees that the nuclear stopping effect gets weaker for peripheral collisions. This is in agreement with the naive expectation that the incident nucleons need to traverse more nucleons in central collisions and lose more energy. Though the values of c are quite small, the little difference can give the difference of the p_T distributions at different pseudo-rapidity η .

After obtaining the values of parameters A , b , c and d in Eq. (4) for the particle distribution, we can get the pseudo-rapidity distribution for different centralities

$$\frac{dN}{d\eta} = 2 \int p_T dp_T \frac{dN}{p_T dp_T d\eta}, \quad (5)$$

where the factor 2 is included for the total number of all charged particles. BRAHMS Collaboration have presented the pseudo-rapidity distributions for 6 centralities [15]. Unfortunately, the centrality cuts in [15] are different from those in [12]. So the obtained parameters shown in TABLE I cannot be used for a comparison of our theoretical expectation and the data on pseudo-rapidity distributions. Furthermore, we would try to calculate the ratio between rapidity distributions for peripheral and

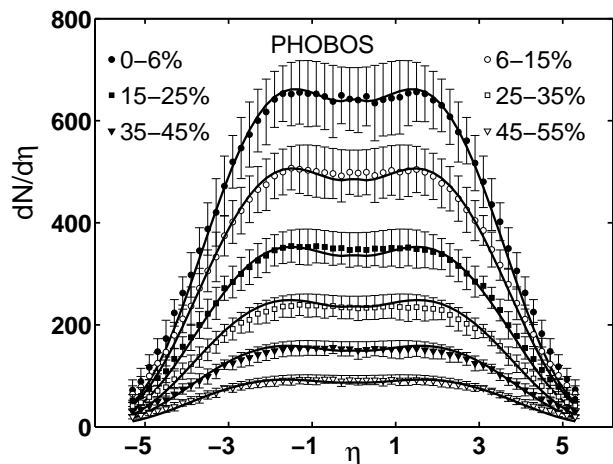


FIG. 2: Fitted invariant charged particle yields as a function of pseudo-rapidity η for six different centralities in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The data points are taken from [16]. Solid curves are from our fitting with Eq. (5).

centrality	A	b	c	d
0 ~ 6%	513.3	0.540	0.21	0.94
6 ~ 15%	387.9	0.540	0.19	0.94
15 ~ 25%	268.6	0.541	0.18	0.94
25 ~ 35%	188.6	0.541	0.175	0.94
35 ~ 45%	119.4	0.542	0.16	0.94
45 ~ 55%	69.4	0.542	0.154	0.94

TABLE II: Values of parameters A , b , c and d for distribution of $dN/d\eta$ for six centrality ranges. The fitted data are taken from [16].

central collisions and compare it with experimental data which is given in [16] by PHOBOS Collaboration. So we now choose to fit the PHOBOS data on rapidity distribution [16]. One should keep in mind that the pseudo-rapidity distribution of charged particles includes contributions from charged particles with all possible transverse momentum for any specific pseudo-rapidity. So soft particles with very low p_T contribute most to η distributions. Since the multiplicity of pions is always much larger than those for protons and kaons when the transverse momentum is integrated, pions always dominate the pseudo-rapidity distribution. For this reason, the mass m in Eq. (5) should be very close to that for pions. So we take $m = m_\pi = 0.139$ GeV in the calculation of the pseudo-rapidity. Because the value of m is different in fitting the p_T and η distributions, other parameters will also be different. However, we will fix $d = 0.94$ in fitting the η distributions. The data on pseudo-rapidity distribution for the charged particle are over the pseudo-rapidity range $-5.4 \leq \eta \leq 5.4$ for six different centrality cuts. The fitted curves are shown in Fig. 2 together with

the data points. The agreement is excellent. The fitted parameters are tabulated in TABLE II. The value of b is almost constant for six centralities, but c decreases faster from central to peripheral collisions than shown in TABLE I. The small increase of parameter b from central to peripheral collisions is responsible for the decrease of the suppression effect for pions in the collisions. Such a trend is opposite to that in TABLE I, because in Fig. 1 protons contribute more in central collisions than in peripheral ones and the production of proton is, instead of being suppressed, enhanced in central collisions. When we focus on the pseudo-rapidity distributions, the effect of c is to narrow the distributions. In our model such effect is mainly from nuclear stopping. The fact that the value of c in TABLE II (where protons play less important role) is much larger than that in TABLE I suggests that the nucleus stopping effect can be illustrated more easily from pion spectra than from proton spectra.

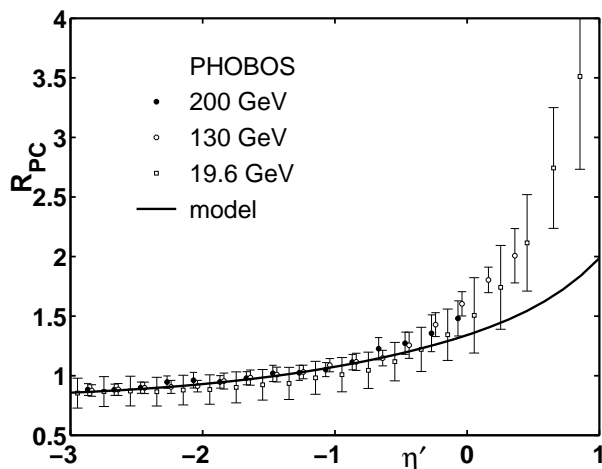


FIG. 3: The ratio R_{PC} of $dN_{ch}/d\eta'$ per participant pair between peripheral (35-40%) and central (0-6%) collisions. The data are taken from [16]. The solid curve is for the calculated results from parameterization Eq. (4) and Eq. (5).

One can go further to the very forward region with pseudo-rapidity $\eta \sim y_{\text{beam}} = 5.36$ for $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions to investigate the centrality dependence of rapidity distributions. To compare the distributions at different colliding energies, a shifted variable is introduced $\eta' = \eta - y_{\text{beam}}$, and an observable

$$R_{PC} = \left(\frac{1}{N_p} \frac{dN}{d\eta} \right)_{35-40\%} / \left(\frac{1}{N_p} \frac{dN}{d\eta} \right)_{0-6\%}$$

is measured in PHOBOS experiment at different colliding energies [16]. With the fitted parameters for the pseudo-rapidity distributions, the ratio R_{PC} can easily be calculated. We use the parameters for centrality cut 35 – 45% in the calculation of R_{PC} , with N_p given in [16], and the obtained results are plotted in Fig. 3 in comparison with the data points with the centrality cut 35 – 40% for the peripheral collisions. Up to $\eta' = 0$ our calculated results agree with the data quite well. For $\eta' > 0$, only data points at $\sqrt{s_{NN}} = 19.6$ GeV are available. In collisions at such a low energy, the contamination from the spectator nucleons to the produced particles in the very forward region is considerably serious, especially for peripheral collisions. This contamination will make R_{PC} larger. That is a possible origin of the discrepancy of our calculated results from the data at large η' . To verify this statement, more deliberate experimental investigations are required.

IV. CONCLUSION

In summary, we have investigated the transverse momentum and pseudo-rapidity dependence of the distribution of charged particle multiply for several centrality ranges, respectively. We assumed a factorized parameterization for the invariant momentum distribution, with the transverse momentum distribution at mid-rapidity being given by a Gaussian form of the transverse rapidity and the longitudinal momentum distribution by a exponential form characterizing the nuclear stopping effect. For the produced charged particles, with suitably chosen effective mass, the simple phenomenological factorized form can fit the experimental p_T and η distributions very well. Then the enhancement of the rapidity distribution for peripheral collisions relative to central ones can be explained naturally for very forward particle production.

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